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The ESA–ESO Working Group on Galactic Populations, Chemistry and Dynamics

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ESA and ESO initiated a series of Working Groups to explore synergies between space- and ground-based instrumentation. The work of the fourth of these Working Groups, described in this article, focuses on Galactic stellar populations, their chemistry and dynamics, and identifies a set of top questions that future missions and/or ground-based facilities will help to answer. Its mandate was to focus on Gaia/ground synergies in the domain of Galactic science. The major recommendations are for ESA to guarantee the expected tremendous capabilities of Gaia, for ESO to consider the construction of highly multiplexed spectrographs for follow-up and complementary observations of selected Gaia targets, and for ESA and ESO to consider jointly ways to give European astronomers a lead in the exploitation of the Gaia catalogue.

As part of the bilateral cooperation between the two organisations, the Executives of ESO and ESA decided "to identify potential synergies within their future projects". ESA and ESO therefore initiated a series of Working Groups (WGs) to explore synergies between space- and ground-based instrumentation in some key scientific areas of astronomy. The first three Working Groups dealt with Extrasolar Planets (Perryman et al., 2005), the Herschel–ALMA Synergies (Wilson & Elbaz, 2006) and Fundamental Cosmology (Peacock et al., 2006). The fourth Working Group, whose report is presented in this article, was decided during the third ESA–ESO bilateral meeting that took place on 25–26 October 2006 at ESO, with the mandate to focus on Gaia/ground synergies in the domain of Galactic science. The Working Group was constituted in April 2007 and is composed of Catherine Turon (Chair), Francesca Primas (Co-Chair), James Binney, Cristina Chiappini, Janet Drew, Amina Helmi, Annie Robin and Sean G. Ryan. A few colleagues also made some further contributions to the report. Three meetings were held in Garching with the efficient support of the ST-ECF, particularly Wolfram Freudling, Bob Fosbury and Britt Sjoeberg. The beautiful cover was designed by the ESO Education and Public Outreach Department, based on the painting *Origine della Via Lattea* by Jacopo Tintoretto (1518–1594) and an artist's impression of the Milky Way (from a NASA/JPL–Caltech press release).

Since the original motivation for this report was a desire on the part of ESO and ESA to consider projects that would complement the Gaia mission in the domain of Galactic science, the panel's expertise is based primarily in stellar and dynamical astronomy and the WG mostly concentrated on Galactic stellar components and on optical observations. The main goal of Galactic science is to understand the formation and further evolution of our Galaxy, and to identify the processes that have shaped, and which continue to shape, its stellar populations and gas content. This implies obtaining a consistent picture of the structure, the dynamics and the chemical characteristics of the different Galactic populations and, when possible, the comparison with the observations made on nearby galaxies in the Local Group, where mean chemical characteristics are different from those in our own Galaxy.

This work was especially timely given the planning currently being undertaken for Gaia by ESA, with a launch foreseen by the end of 2011, and the impending first-light of dedicated survey telescopes in the optical and near-infrared by ESO (VISTA by the end of 2008 and VST in 2009). Moreover, in the future E-ELT era, new utilisation of 4- and 8-metre telescopes and instrumentation can be envisaged.

The context

In this context, a few remarks should be highlighted:

– the volume and quality of data that Gaia will provide will revolutionise the study of the Galaxy even more than Hipparcos revolutionised the study of the Solar Neighbourhood;

– there is a need for very large statistically-significant samples to undertake many of the dynamical, kinematic and compositional studies of the Galaxy, and surveys are ideal tools in this respect;

– it will be important to develop the capabilities to cover what Gaia will not, such as high resolution spectroscopic follow-up for a large number of targets selected from Gaia data, medium resolution spectroscopy for a large number of selected faint stars for which no spectroscopic data will be obtained from Gaia, or achieving wide wavelength coverage in photometry and spectroscopy;

– advances in infrared (IR) astronomy will allow us to tap the benefits of infrared wavelengths for astrometric, spectroscopic and photometric observations of the obscured Galactic Bulge and the central region of the Galaxy;

– stellar population science needs access to visible (including blue) spectra of stars in the Galaxy, and not just to the infrared (IR) that is favoured for much cosmological work;

– proper interpretation of such a huge mass of data demands significant improvements to underlying theory, modelling and analysis techniques.

The top questions in Galactic science

Much has been learned about the various components of the Galaxy since the early 1940s when Walter Baade introduced the concept of stellar populations, but we still have a fragmentary picture of how the Galaxy was assembled and subsequently evolved. Only the concomitant availability of high quality data on distances, kinematics, ages, physical parameters and element abundances for sufficiently large samples of stars from each of the Galaxy components would have a profound impact on our views of how the Galaxy formed and evolved. It is, in particular, crucial to obtain observations at various distances from the Galactic Centre and various distances from the Galactic Plane, from the Galactic Bulge out to the external parts of the Disc and the halo, including stars in all kinds of substructures such as OB clusters and associations, globular clusters and streams.

The first and main task of the Working Group has been to review the state-of-the-art knowledge of the Milky Way galaxy, to identify the future challenges, and to propose which tools (in terms of facilities, infrastructures, instruments, science policies) would be needed to successfully tackle and solve the remaining open questions. In Section 3 of the report we examine the current state of our knowledge in Galactic science: the main structures of the Galaxy; the continuing process of star formation that strongly shapes its present-day properties; the dynamics of stars that are the clue to determining the mass distribution in the Galaxy, connecting the kinematics of each population with its spatial distribution and relating the present orbits of stars to the orbits on which they were born; the basic astrophysical parameters (ages, kinematics and chemical abundances) from which stellar evolution can be inferred. Finally, at the end of Section 3 we sketch the current picture of how the Galaxy was assembled from its building blocks.

In Section 4 of the report we describe how the Galaxy can be used as a laboratory in which to study the processes that shape galaxies, and to constrain theoretical models of galaxy formation and evolution. In the course of Sections 3 and 4, we identify a number of limits on our current knowledge, and hint at future work that would overcome these. These issues are brought into sharp focus in Section 5, where we identify the top remaining questions, and suggest how possible solutions might be provided by investment in new facilities, planned and yet to be planned. In that section, we first identify the eight top global questions, related to the Galaxy as a whole: Which stars form and have been formed where? What is the mass distribution throughout the Galaxy? What is the spiral structure of our Galaxy? How is mass cycled through the Galaxy? How universal is the initial mass function? What is the impact of metal-free stars on Galaxy evolution? What is the merging history of the Galaxy? Is the Galaxy consistent with ΛCDM? Then we consider the top open questions for each of the main components of the Galaxy. In Section 6 we review ground- and space-based facilities that have played and/or will play a major role in achieving our scientific goals. Detailed recommendations of the Working Group are drawn together in Section 7.

Figure 1. The front cover to the 4th ESA–ESO Working Group Report, designed by the ESO Education and Public Outreach group, is shown. A detail from the painting of Jacopo Tintoretto is blended with an artist's impression of the Galaxy. Jacopo Tintoretto (1518–1594) was a Venetian painter of the Italian Renaissance, renowned for his dramatic use of light, shadows and bright colours. The painting is the *Origine della Via Lattea* showing how the Milky Way was created from the milk of Hera. Zeus, wishing to immortalise his baby Heracles, born from a mortal woman, Alcmene, held him to the breast of Hera, who was sleeping. She suddenly awoke and pushed away the unknown infant. The milk spurting towards heaven became the Milky Way, while some drops fell downwards giving rise to lilies. The painting is currently located in the National Gallery, London. The artist's impression of the Galaxy was designed to illustrate new observations from NASA's Spitzer Space Telescope revealing that the Galaxy might have only two major arms of stars rather than four as was previously believed (see *http://www.spitzer.caltech.edu*).

Recommendations

Europe has led the way in Galactic research as regards astrometry and spectroscopy and is on the brink of taking the lead in photometry: ESA's Hipparcos mission pioneered space astrometry and paved the way for the ambitious Gaia mission, which will perform the first parallax survey down to magnitude $V = 20$ in parallel with a complete characterisation of each observed object; ESO's innovative telescopes (NTT and VLT) coupled to leading capabilities in the construction of multi-object spectrographs have yielded detailed stellar abundances of faint stars; ESO is about to start massive programmes of optical/near-IR photometry with two dedicated survey telescopes (VISTA and VST). This observational work is backed by unique European expertise in modelling stars and galaxies (stellar atmospheres, stellar and galactic evolution, population synthesis, dynamics, etc.).

The opportunities for European science are tremendous if we make strenuous efforts to capitalise fully on these assets. This involves taking both full advantage of the instrumentation that we have and planning new facilities. Particular attention has to be paid to the optimisation of synergies between Gaia and ground-based observations, especially with the present or potential ESO instruments.

The major recommendations from this Working Group are as follows:

1. For ESA to make maximum effort to guarantee the expected tremendous capabilities of Gaia (accuracies and limiting magnitudes for the astrometric, photometric and spectroscopic aspects of the mission). Only if these requirements are fulfilled can the satellite provide the promised revolution in our knowledge of the Galaxy by unveiling populations through the study of chemistry and dynamics.

2. For ESO to consider facilities (construction of new highly multiplexed wide field spectrographs or improvement of the capabilities of existing instruments) for medium to high resolution spectroscopic observations of a large number (40 000–100 000) of particularly interesting stars selected from Gaia observations. There are two aspects to this recommendation:

– Follow-up observations. Gaia will be a fantastic tool to select well-defined and unbiased samples of targeted stellar populations. High resolution spectroscopy (in the blue for the halo and thick disc stars, in the red and with more fibres for the thin disc and Bulge) will provide detailed abundances.

– Complementary observations. Medium resolution spectral observations will provide radial velocities and metallicities for selected samples of stars fainter than $V = 16.5$, not measured by the Radial Velocity Spectrometer (RVS) on-board Gaia.

The recommended instruments are as follows:

a) Blue multiplexed spectrograph on a 4 or 8 m-class telescope, with more than 100 fibres, high blue sensitivity (signal-to-noise, S/N ~ 30–40) and high resolving power (20 000–30 000), to measure detailed abundances in 20 000–50 000 halo, thick-disc and outer thin-disc stars. This could be either on a dedicated 8 m-class telescope with field of view (FOV) ~ 0.5 deg^2, or on a dedicated 4 m telescope with FOV ~ 2.5 deg^2.

b) Infrared highly multiplexed spectrograph to be placed on a dedicated 4 m-class telescope, with AO correction, massive multiplexing (> 500 fibres), S/N ~ 20–30, high resolving power (20 000–30 000) and large field of view. This instrument would obtain detailed abundances and radial velocities for 20 000–50 000 obscured Bulge, thin-disc stars. A lower resolution mode (R ~ 4000) would also be perfect for fainter targets, not observed by the RVS on board Gaia. ESO may also consider collaboration with teams starting the development of such instruments (APOGEE in the USA; WINERED in Japan; UKIDNA or HERMES in Australia).

c) Infrared multiplexed spectrograph on an 8 m-class telescope. ESO should consider improving the capabilities of current VLT multiplexed spectrographs for a larger field of view and at IR wavelengths.

3. For ESA and ESO jointly:

– Calibration of Gaia instruments. ESA and ESO should jointly facilitate observations with ESO telescopes that are required for the calibration of Gaia instruments.

– European leadership in the exploitation of Gaia data. ESA and ESO should jointly consider ways to give European astronomers a lead in the exploitation of the Gaia catalogue and facilitate follow-up observations on a "targets to be specified later" basis.

Other recommendations

1. For ESA:

– Prepare for the future of astrometry.

a) Infrared astrometry would be the ideal complement to Gaia, which is not able to observe deeply in the Galactic Centre, the Bulge and parts of the Disc because of heavy extinction and crowding. The ideal instrument would achieve an astrometric accuracy of 10 µas down to magnitude 17 in the 0.9 µm z-band. A first step in this direction might be a collaboration with the Japanese project JASMINE (10 µas astrometric accuracy for stars brighter than $z = 14$).

b) Microarcsecond accuracy astrometry in the optical (better than 4 µas). This is the requirement for resolving the internal motions of the outer globular clusters and dwarf galaxies of the Local Group, for which Gaia will provide only mean motions. This capability would also enable us to obtain direct distances to extragalactic stellar candles.

– Asteroseismology. This is a major tool to complement Gaia with respect to age determination. ESA should encourage the community to prepare for a next-generation mission, which would sample all stellar populations of the Galaxy.

– UV spectroscopy. UV wavelengths are now only accessible through the Hubble Space Telescope (HST). ESA should support the longevity of Hubble, with a substantial share of its observing time being devoted to UV instruments, and support the use of COS, the new UV spectrograph to be installed on HST during the fourth Servicing Mission.

2. For ESO:

– Spectrograph on the E-ELT. ESO should consider a spectrograph with very high resolving power (40 000–70 000) on the E-ELT to observe abundances of stars (Population II and III stars, F- and G- dwarfs, etc.) across the whole disc and far from the Solar vicinity (Bulge, outer Halo).

– Near-IR photometric survey. It would be very valuable for the Southern Galactic Plane area as well the innermost regions of the Galaxy to have full near-IR coverage. The different VISTA surveys will be an important first step in this direction, but their final goals might be different. ESO should closely follow the sky and wavelength coverage of these surveys, and eventually invest extra observational efforts to ensure total coverage.

3. For ESA and ESO jointly:

– Observation of the fine structure of the ISM. Support proposals to use ALMA/Herschel observations to study the fine structure of the interstellar medium (ISM).

– Enhance the European scientific return from large Galactic surveys by sponsoring actions that would optimise the performance of the European astronomical community in mining these data:

  a) Workshops on modelling and theory for stellar interiors and atmospheres; stellar evolution including that of massive stars and binaries; stellar population synthesis; galactic dynamics and specific models of Galactic populations; the interstellar medium and the distribution of dust and gas in the Galaxy.

  b) Fellowships, aimed at both improving the underlying theory and modelling and developing high performance analysis techniques.

– Further ESA–ESO Working Groups:

  a) Star formation in various environments. This topic will have a strong impetus with the start of the ESO public surveys of the Galactic Plane, the launch of Herschel, and the progressive and massive enhancement of sub-mm observations with ALMA.

  b) Galaxy formation. The diverse instruments considered for the E-ELT are in their definition phases and it is appropriate to explore fully the possible synergies between E-ELT and JWST instruments in order to explore in detail the whole Galaxy and its outskirts, in particular the *Terra Incognita* behind the Galactic Centre.

As a conclusion, ESA and ESO are providing European astronomers with unique instruments, opening the way to extremely high accuracy space astrometry and innovative ground-based telescopes, equipped in particular with first-class spectrographs. The main recommendation of this report is for the two organisations jointly to organise vigorously the exploitation of synergies between Gaia and ground-based observations, and consider ways to give European astronomers a lead in the exploitation of the Gaia catalogue.

References

Peacock, J. A. et al. 2006, ESA–ESO Working Group Report on Fundamental Cosmology

Perryman, M. et al. 2005, ESA–ESO Working Group Report on Extrasolar Planets

Wilson, T. L. & Elbaz, D. 2006, ESA–ESO Working Group Report on The Herschel–ALMA Synergies

Links

Spitzer release: *http://www.spitzer.caltech.edu/Media/releases/ssc2008-10/release.shtml*

Working Group Report: *http://www.stecf.org/coordination/eso-esa/galpops.php*

To request a printed copy of the report, please contact Britt Sjoeberg (*bsjoeber@eso.org*).

L'Harmonie des Spheres

CD of Organ Music for IYA2009

Music of the Spheres is the title of a CD by the French astrophysicist Dominique Proust. As well as being a regular observer at La Silla and Paranal he has given organ concerts at Santiago, Valparaiso, La Serena as well as at La Silla.

The CD contains 12 organ pieces directly inspired by astronomy, including the planetary harmonic scale of the *Harmonices Mundi* from Joannes Kepler, a *Dialogo* from Vicenze Galilei (father of the astronomer), a fugue by the famous astronomer William Herschel, *Jupiter* from Gustav Holst's *The Planets*, variations on the chorale *How bright is the morning star* from Johann Sebastian Bach and other pieces. The CD has been produced with the support of the AMA2009 (Année Mondial de l'Astronomie) committee and is available on request from Dominique Proust (*dominique.proust@obspm.fr*). Benefits will be donated to a charitable association.